

# X-56A Structural Dynamics Ground Testing Overview and Lessons Learned

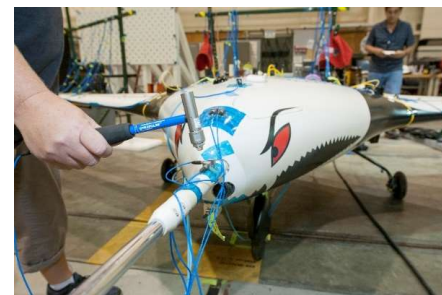
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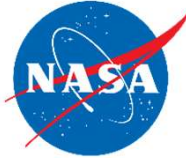
January 6<sup>th</sup>-10<sup>th</sup> 2020



Advanced Air Vehicles Program  
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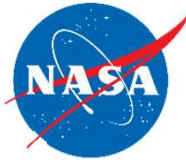
# Outline

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- Background and Motivation
- Ground Vibration Testing
  - Troubleshooting and Resolution
- Moment of Inertia Testing
- Lessons Learned

# Background and Motivation



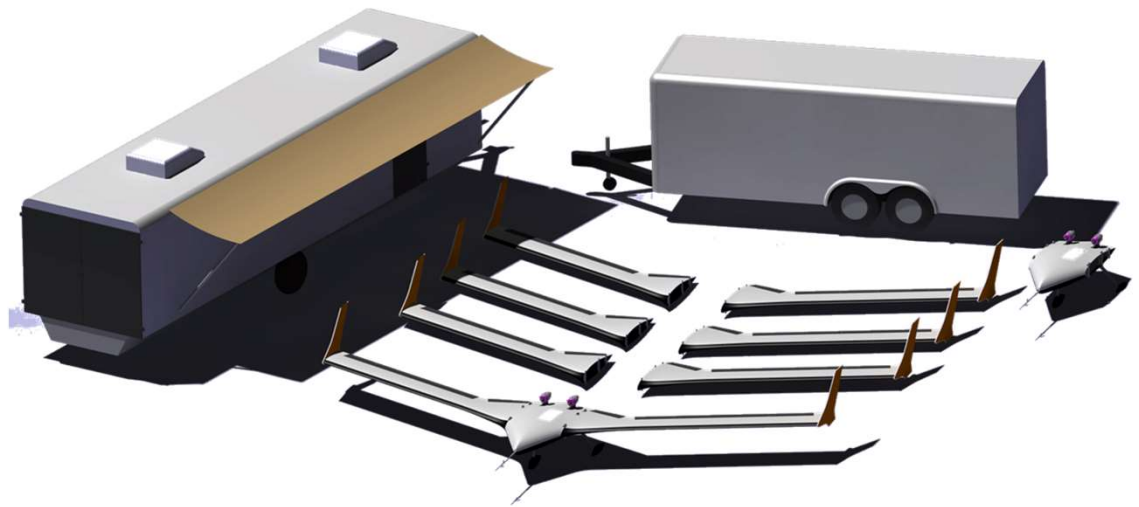
- Next generation aircraft will incorporate cutting-edge technologies that enable higher performance, while increasing structural efficiency through weight reduction.
- However, reducing weight often means reduced stiffness in the structure. Increased flexibility can make aircraft more vulnerable to various aeroelastic phenomena, such as flutter, buffet, buzz, divergence, and adverse gust response.
- The X-56 research vehicle is designed as a high risk aeroelastic aircraft to demonstrate active flutter suppression and gust load alleviation.
- Accurate structural modeling is critical for successful control of a highly flexible aircraft.



# X-56 Research Vehicle

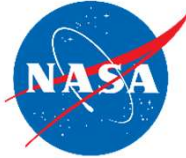


- Funded by Air Force Research Laboratory
- Designed by Lockheed Martin Skunkworks
- Delivered to NASA for continued research efforts
- Complete Research System
  - 2 Center Bodies (Fido and Buckeye)
  - 1 Stiff Wing Set
  - 3 Flexible Wing Sets
  - 1 Ground Control Station



# Structural Dynamics Ground Testing

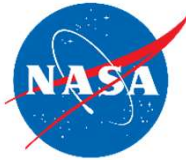
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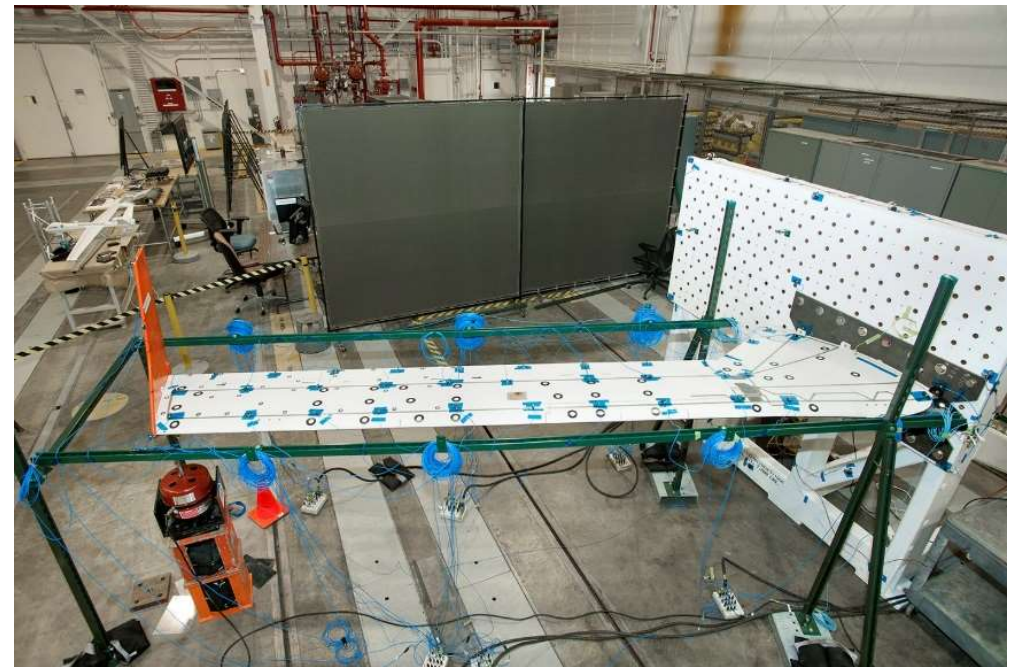
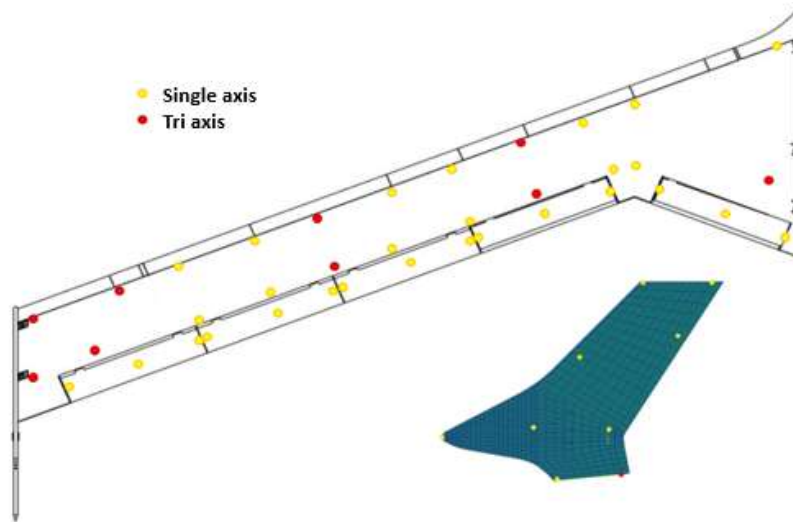
- Lockheed Martin performed initial series of ground tests on Fido centerbody and wing sets
- NASA performed additional series of structural tests on Buckeye centerbody and wing set to address potential fabrication differences and configuration changes
- Buckeye fuselage had increased mass, change in mass distribution, shift in CG
- Wings were made from different batches of composite materials. Needed to verify consistency of fabrication.
- Required high confidence in finite element model (FEM) due to its integral role for developing models directly used in controller development



# Wing-only Strongback GVT

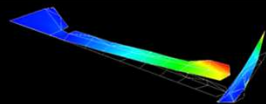
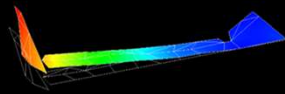
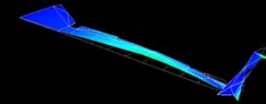
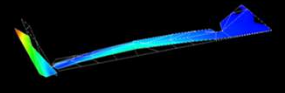
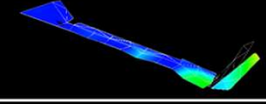
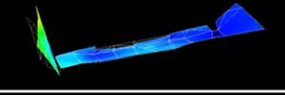
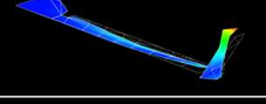
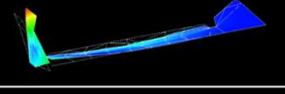
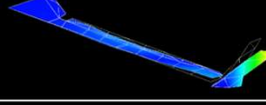
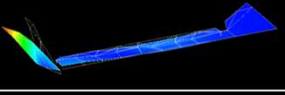
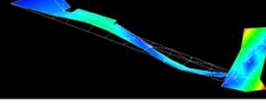
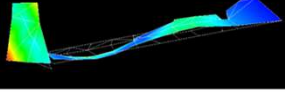


- Compare and validate frequency response of both left and right wings.
- Determine any manufacturing differences.



# Wing-only GVT results



Mode number	Mode shape (left wing)	Mode shape (right wing)	Frequency difference between left and right wing, %
1			-0.73
2			0.86
3			-0.12
4			0.08
5			4.54
6			3.36

**Conclusion:** The left and right wings had similar structural dynamic properties

# Full Vehicle Ground Vibration Test



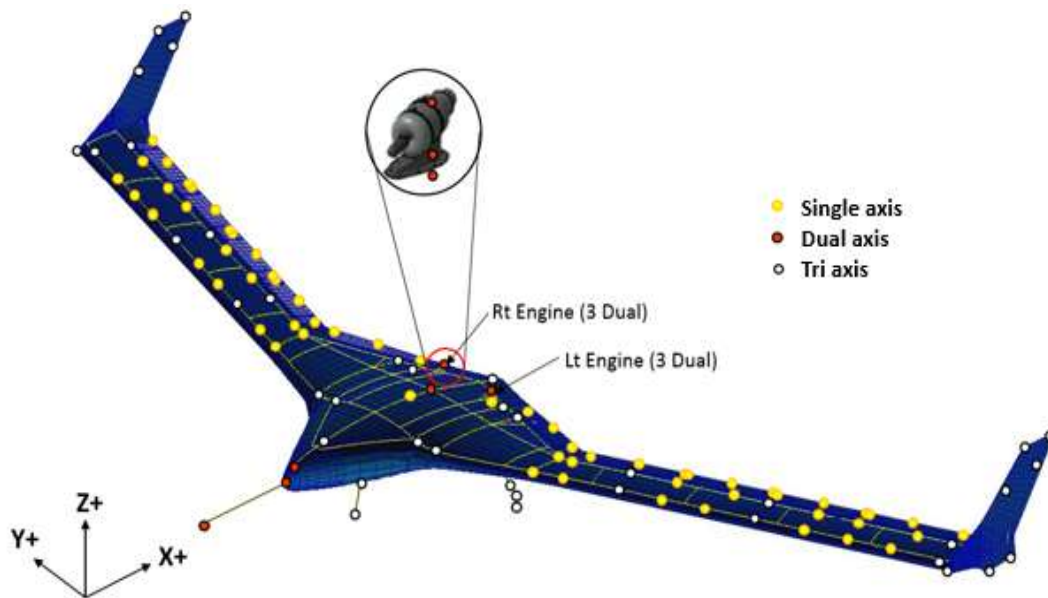
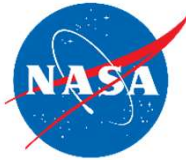
- Conducted multiple GVTs in different aircraft, test, and fuel configurations
- Acquired damping, frequency, and mode shape for each GVT test configuration
- Data used for FEM model update and tuning in order to reduce model uncertainties between numerical and experimental modal data



**Free – Free Full Fuel Configuration:  
One Bungee Suspension Assembly**

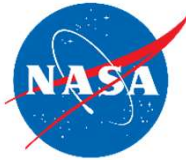


# X-56A Aircraft GVT Data Collection

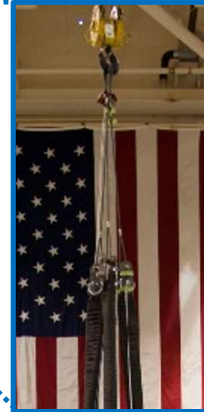


- GVT accelerometers
  - 119 accelerometer locations
  - 227 aircraft channels
  - 32 soft support system channels
- FOSS
- High-speed photogrammetry
  - Only for the left wing
  - 250 frames/sec
- Aircraft flight accelerometers

# Progression of Soft Support Set-up



Challenges in the soft support boundary condition:



**Original Three Bungee Suspension System with Spreader Bar**



**Modified Three Bungee Suspension System without Spreader Bar**



**Single Bungee Suspension System**

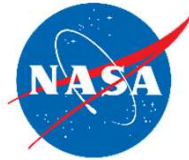
# Primary Mode Shapes



Mode number	GVT mode shape	Difference between FEM and test: Empty fuel, percent	Difference between FEM and test: Full fuel, percent
1	Symmetric Wing 1 <sup>st</sup> Bending (SW1B)	-6.09	2.01
2	Antisymmetric Wing 1 <sup>st</sup> Bending (AW1B)	-6.39	-3.31
3	Symmetric Wing 1 <sup>st</sup> Torsion (SW1T)	-0.62	0.36
4	Symmetric Fore-Aft (SFA)	-0.04	-1.25
5	Antisymmetric Wing 1 <sup>st</sup> Torsion (AW1T)	1.63	1.27
6	Symmetric Wing 2 <sup>nd</sup> Bending (SW2B)	-1.31	-0.21

Mode number	Mode shape (FEM)	Mode shape (test)
1 SW1B		
2 AW1B		
3 SW1T		
4 SFA		
5 AW1T		
6 SW2B		

# GVT Data Troubleshooting



- Added fuel mass should **decrease** the first bending frequency due to increased inertia
- Frequency shift from fuel weight was observed in the FEM and during subsequent flights
- The fuselage contributes significantly to the SW1B mode; therefore any external factors that can affect the fuselage dynamics can affect SW1B

## Empty Fuel

Mode #	Mode	GVT (normalized freq)	FEM (normalized freq)
7	SW1B	1.000	1.061
8	AW1B	1.622	1.726
9	SW1T	3.561	3.539
10	SFA	4.001	4.000
11	AW1T	4.190	4.122

- Primary Mode
- Secondary Mode

## Full Fuel

Mode #	Mode	GVT (normalized freq)	FEM (normaliz ed freq)
7	SW1B	0.997	0.977
8	AW1B	1.659	1.714
9	SW1T	3.539	3.526
10	SFA	3.901	3.950
11	AW1T	4.166	4.113

% Frequency Shift due to Fuel Load	
GVT	FEM
-0.33%	-7.93%
2.25%	-0.71%
-0.63%	-0.37%
-2.50%	-1.25%
-0.58%	-0.21%

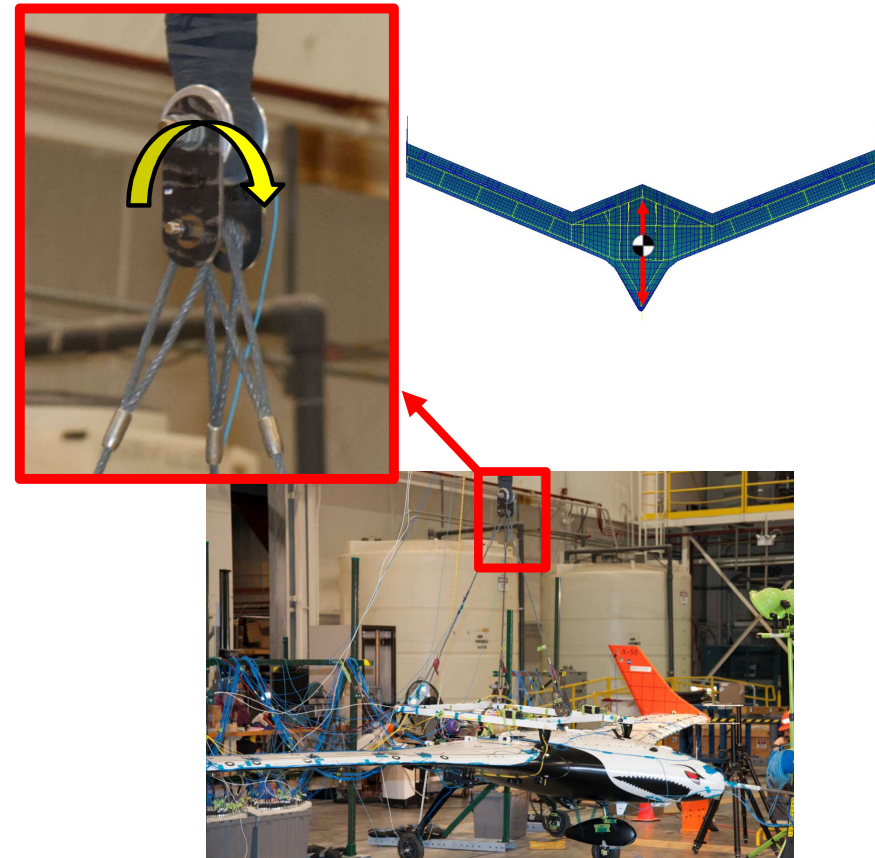
### Notes:

- \* Free-Free GVT results calculated from single bungee configuration.
- \* Baseline FEM only models vehicle, no GVT lifting hardware is included
- \* All frequencies are normalized with respect to measured SW1B empty fuel

# Bungee Set-up Scrutinized

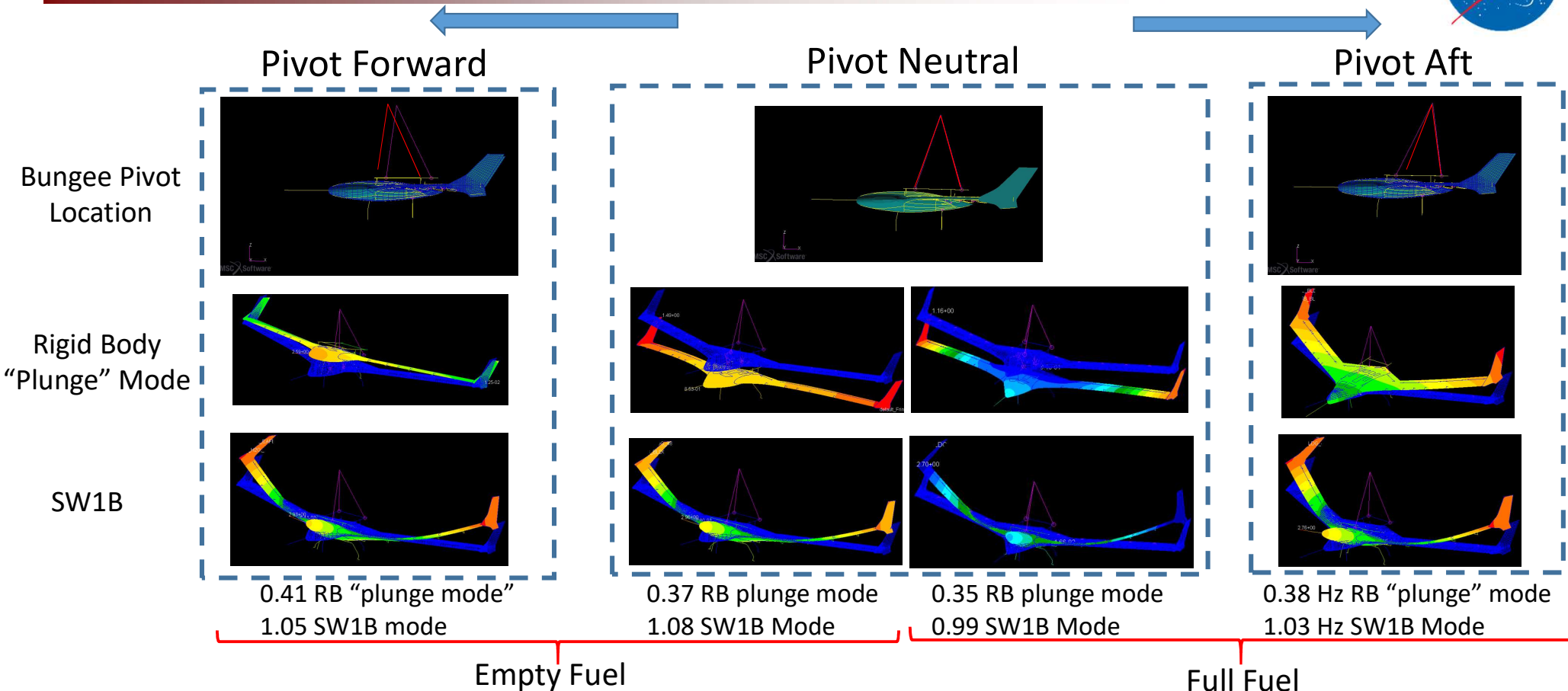
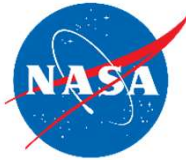


- Vehicle was still free to pivot about sling-bungee connection (offset vehicle Y-axis)
- $X_{CG}$  (fore-aft) of the vehicle shifts along the direction of the vehicle pitching motion between the empty and full fuel condition
- Metal wire slings will readjust attitude of vehicle to ensure vehicle CG is directly below bungee
- A sensitivity analysis on the bungee X-location was performed to determine its affect on rigid body and flexible modes





# Varying FEM Bungee Pivot Point Results



SW1B frequencies approach each other when changing pivot location to account for CG shift

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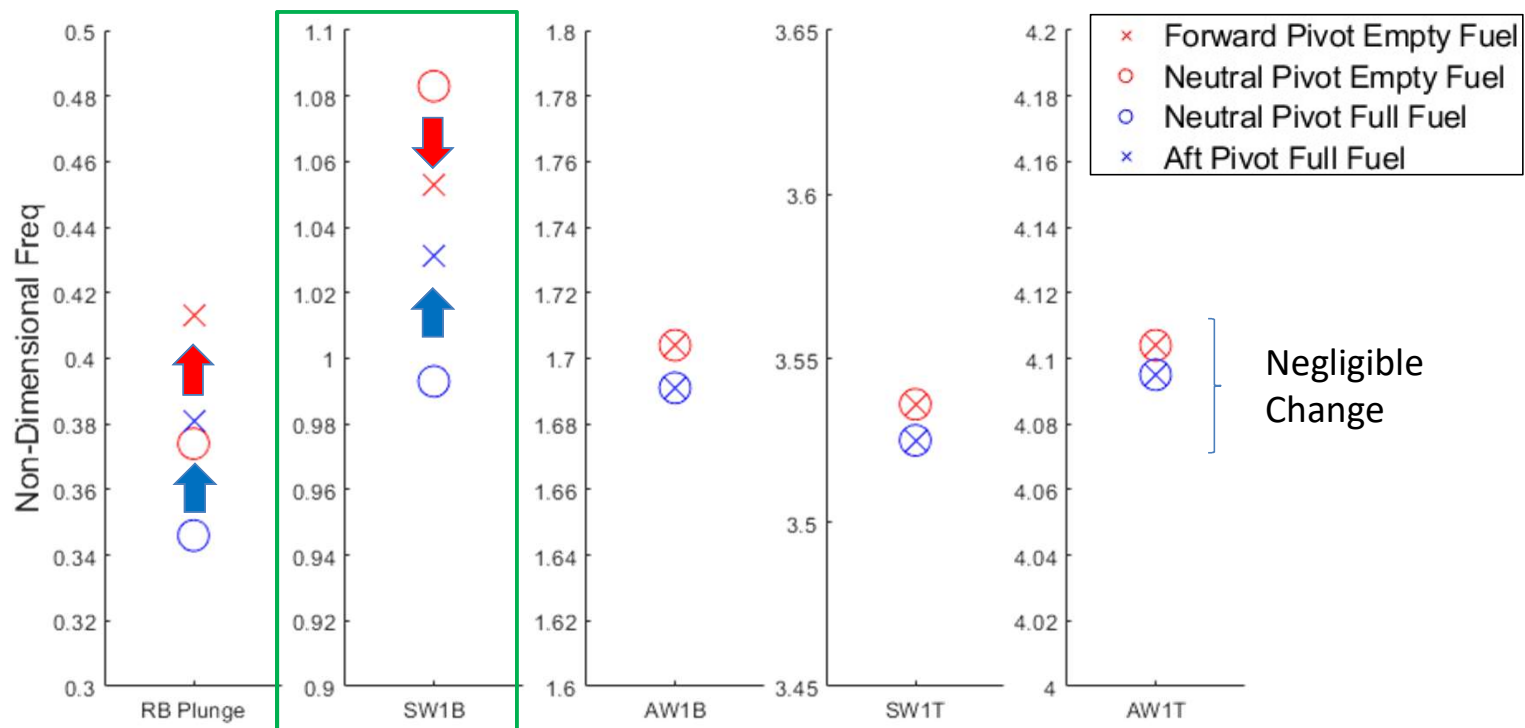
\* All frequencies are normalized with respect to measured SW1B empty fuel

# Examining other flexible modes



- Only the SW1B and rigid body plunge mode changes when fore-aft (X) location of pivot changes.
- Pivot location negligibly affects other primary flexible modes

Approaches same frequency for SW1B



# Moment of Inertia Test

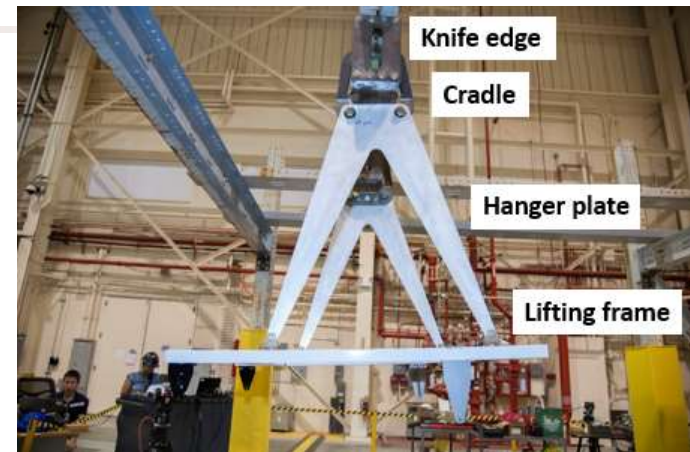
Objective: Measure pitch MOI using compound pendulum method

$$I_{yy\_vehicle} = \frac{w_1 T_1^2 L_1}{4\pi^2} - \frac{w_2 T_2^2 L_2}{4\pi^2} - \frac{w_3 L_3^2}{g}$$

Configuration	Description	Pendulum length	Fuel condition
A	Lifting hardware only	Long	N/A
B	Lifting hardware only	Short	N/A
C	X-56A + lifting hardware	Short	Empty
D	X-56A + lifting hardware	Long	Empty

Calculated pitch moment of inertia was within 2.5% between short and long pendulum configurations

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**MOI Test Configuration**



# Lessons Learned



## **Wing-only Strongback Ground Vibration Test:**

- Install additional tri-axial accelerometers at the winglet for better resolution of mode shapes.
- Power-on actuators to prevent drooping from excitations.

## **Full-Aircraft Ground Vibration Test:**

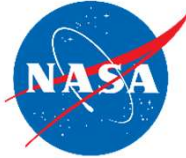
- Additional scrutiny is required when using multiple bungees because of the increased risk of coupling between bungees or with the rigid-body modes of the flexible vehicle.
- Eliminate all potential degrees of freedom (that is, the metal sling rotation around the bungee) that could interfere with the rigid-body structural modes.
- Perform pre-test analysis with various boundary conditions to identify potential boundary-condition sensitivities for obtaining quality data.
- When possible, instrument the soft-support system (bungees and hardware) to verify their independence from the structural modes and to assist with any required troubleshooting.
- Ensure that the bungees are sufficiently flexible, and minimize interference in all degrees of freedom of interest.

## **Aircraft Pitch Moment of Inertia Test:**

- When using knife-edges, curved-out V-channels further reduce friction.
- Use multiple sources for period measurement as a sanity check for accurate data.

# Acknowledgements

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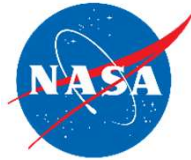


- NASA Aeronautics Advanced Air Vehicles Program and the Advanced Air Transport Technology Project
- Air Force Research Lab
- Lockheed Martin Skunkworks
- Armstrong Flight Loads Lab
- ATA Engineering





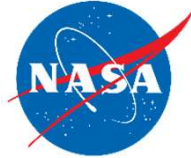
# Questions



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# Backup Reference Slides



# X-56A Aircraft GVT Excitation Cases

- Shaker

- Left & Right wings (45° & 90°)
- Fuselage Fwd (Vert & Lat)
- Fuselage Aft (Vert)

- Impact Hammer

- Nose boom (Vert & Lat)
- Nose landing gear (Fwd/Aft & Lat)
- Main landing gear (Fwd/Aft & Lat)
- Engines (Lat)
- Left & Right wings (Vert)

Shaker



Impact Hammer





- Primary Modes:
  - Symmetric Wing 1st Bending (SW1B)
  - Antisymmetric Wing 1st Bending (AW1B)
  - Symmetric Wing 1st Torsion (SW1T)
  - Antisymmetric Wing 1st Torsion (AW1T)
- Secondary Modes
  - Symmetric Wing 1st Bending and Symmetry Main Landing Gear Lateral (SW1B & S MLG Lat)
  - Antisymmetric Wing 1st Bending Lateral and Antisymmetric Winglets (A MLG Lat & AWL)